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Prevention of Derailments due to Concrete Tie Rail Seat Deterioration

John Choros
Mechanical Engineer
Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142
Phone (617) 494-2855; Fax (617) 494-3616.
choros@volpe.dot.gov

Michael N. Coltman
Division Chief
Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142
Phone (617) 494-2591; Fax (617) 494-3616.
coltman@volpe.dot.gov

Brian Marquis
Mechanical Engineer
Volpe National Transportation Systems Center
55 Broadway
Cambridge, MA 02142
Phone (617) 494-2922; Fax (617) 494-3616.
marquies@volpe.dot.gov

ABSTRACT

Concrete tie rail seat abrasion/deterioration (RSA) has been an issue since the inception of concrete ties. As a result of recent derailments involving abraded concrete ties on curved track, the Federal Railroad Administration set up a task force to study abrasion/deterioration mechanisms and develop automated detection methods using existing research vehicles. A portion of this study reviews historical development of concrete abrasion due to moisture or foreign materials incorporated under the rail seat that tend to abrade concrete ties evenly across the rail seat area. This report discusses a newly identified concrete tie deterioration mechanism characterized by material loss in a triangle toward the field side of the rail seat, resulting from wheel rail interaction involving track geometry variations.

The NUCARS™ model was used to evaluate the vertical and lateral loading at one of the recent derailment sites using the track geometry measured approximately one month before the derailment. Wheel loads predicted from the model, based on P-42 Amtrak Locomotive, were used to evaluate the pressure distribution at the rail concrete tie interface and were compared with allowable design bearing pressure for concrete used in the manufacture of concrete ties. The results indicate that applied stress on the field side of a concrete tie due to outward rail roll can exceed the design values. Applied pressure distribution exceeding the design strength on the field side tends to abrade concrete ties in a triangular wear pattern that produces wide gage. Charts were developed to convert measured field side abrasion/deterioration to additional gage widening under an applied vertical load for identifying critical locations with wide gage defects. Further, techniques for field inspectors to detect, measure, and evaluate rail seat abrasion/deterioration (RSA) based on commonly used inspection technology are discussed.

INTRODUCTION

The Federal Railroad Administration (FRA), with assistance from the Volpe National Transportation Systems Center (Volpe Center), has been conducting research on rail seat abrasion/deterioration and methods to measure and prevent derailments. As a result of two Amtrak derailments, FRA has set up a task force to evaluate the cause of the derailments and to address methods of preventing future derailments due to rail seat abrasion. The task force consists of FRA personnel from the Office of Safety, Headquarters and Regions, and Office of Research & Development. Other organizations at the inception of the task force were Volpe National Transportation System Center (Volpe), BNFS Railroad and ENSCO Inc. Additional originations added recently to the task force are the Association of American Railroad (AAR) and Transportation Technology Center, Inc. (TTCI).

Among the key issues considered by the task force, was to understand the forces and the reaction to those forces as they affect rail seat abrasion. This involved reviewing the evolution of concrete ties on North American railway; reviewing research in the area of rail seat abrasion;

modeling the loading environment at the derailment site based on track geometry data taken prior to the derailment; calculating concrete tie stresses and distribution; developing field measurement technologies; and develop charts to readily determine additional gage widening based on measured rail seat abrasion. This paper covers the task forces efforts to address elements of the RSA problems.

New Failure Mechanism

Recently a new form of rail seat abrasion was noted on high curvature territory that is believed to be attributed to excessive compression forces on the rail seat area. The wear patterns in these locations have a triangular shape when viewed from the side of the tie. This wear patterns is similar in shape to the rail seat pressure distribution calculated when a vertical load and overturning moment are applied at the centerline of the rail base. The high vertical and lateral forces applied to the high rail by a curving vehicle provide such a vertical load and overturning moment that loads the rail base unevenly.

Evidence indicate that once this pattern develops and moves beyond the two thirds point of the rail seat width, as referenced from the gage side, high compressive forces develop on the field side of the rail seat. These forces are high even in the absence of an overturning moment since the rail is now bearing on only a fraction of the original bearing area. Further, it is believed that once the rail seat wears to this “triangular” shape the degradation rate is accelerated due to the shift in the contact point toward the field side of the neutral axis.

Background

The use of concrete ties in the railway industry, either experimentally or under revenue service, dates back to 1893. The first railroad to use concrete ties was the Reading Company in Germantown, PA [1]. In 1961, the Association of American Railroads (AAR) [2, 3] carried out comprehensive laboratory and field tests on pre-stressed concrete tie performance. Replacing timber ties with concrete ties on a one to one basis at 19.5 inches spacing proved acceptable based on engineering performance but was uneconomical. Increasing tie spacing from the conventional 20 to 30 inches increased the rail bending stress and the load that each individual tie transfers to the ballast. However, the increased rail bending stress was within design limits. Further, by increasing the tie base width to 12 inches the tie ballast interface pressure was maintained the same as for timber ties. Thus, by increasing concrete tie spacing while maintaining rail, tie, and ballast stresses at acceptable levels, the initial research showed that fewer concrete ties could be utilized making their application more economical alternative to timber ties.

Renewed efforts on the use of concrete ties in the United States in the 1970’s were spearheaded by a major research effort at the Portland Cement Association (PCA) laboratories to optimize tie design. The research included the use of various shapes, sizes, and materials to develop the most economically desirable concrete tie possible. During that time, Construction Technologies Laboratory (CTL), a subsidiary of PCA, also addressed several of the initial concrete design problems including quality control and rail seat abrasion.

Early research efforts [4] in the 60’s and 70’s were focused on the strength characteristics of concrete ties i.e., bending at the top center and rail seat bottom of concrete tie, material optimization such as aggregate and prestressing tendons and concrete failure at the rail-tie and ballast-tie interface. Abrasion or failure of the concrete surface between the rail and ties became apparent when large sections of track were converted to concrete ties, especially on high curvature and tonnage territories. This phenomenon commonly termed “rail seat abrasion,” was noted in one form or another in North America on four major railroads: Canadian Pacific (CP), Canadian National (CN), BNSF, and Union Pacific (UP) [5].” CN’s concrete tie program started in 1976 and researches noted rail seat abrasion of less than 0.2 inch by 1991. In a few cases especially on curved territory, abrasion of as much as one inch has been noted while in the majority of cases, especially in tangent or light curvature track, abrasion was uniform across the rail-tie interface, commonly referred to as the rail seat. BNSF started their program in 1986 and noted the same pattern of abrasion as CN with most of the abrasion occurring on curves. At UP rail seat abrasion was present on 5° curves or greater and CP used a bonded pad to reduce rail seat abrasion. CP’s experience indicated that shortly after the bonded pad failed there was evidence of abrasion. At other concrete tie test sites with less severe environments of curvature, loading and moisture there were no apparent signs of rail seat abrasion.

Mechanisms that lead to abrasion include the potential development of abrasive slurry between the rail pad and the concrete tie. Various materials found in the slurry include dust particles, fine particles from ballast breakdown, debries from rail grinders, and wind blown sand or sand from locomotives. These particles form a slurry when moisture is added. When driven by the rail movement the slurry abrades the concrete surface leaving the concrete aggregate exposed and generating concentrated forces on the rail pad. This abrasion process is accelerated once the pad is substantially degraded and the rail base makes direct contact with the concrete tie.

One common requirement for the development of this failure mechanism is the presence of moisture between the rail pad and the concrete tie surface. In areas with low moisture, concrete abrasion has not been a problem.

Once the problem of rail seat abrasion occurs, the only feasible method of repair is to fill the abraded area with epoxy or another rapidly hardening material that will allow the opening of the line to traffic within a short time. The best and quicker solution would be to replace the individual concrete ties but this could prove uneconomical.

Design of stronger pads that do not allow foreign material and moisture to get under the rail seat is one method of preventing the problem. Sandwiching elastomeric material between steel plates providing higher bearing strength at the two interfaces, rail-pad and pad–tie, is another attempt by the suppliers and the railway industry to prevent rail seat abrasion.

Current Research Efforts

Research efforts in rail seat abrasion are currently conducted by the manufactures of concrete ties and rail seat pads on a proprietary basis. Their efforts are focused on increasing the durability of the pad and preventing moisture from the pad tie interface. AAR through its institutional research support at TTCI is currently conducting research on alterative materials for railroad ties, but due to recent requests by member roads, they are considering refocusing their research efforts to rail seat abrasion. The form of these research efforts and areas of focus are to be determined.

RAIL SEAT PRESSURE DISTRIBUTION ON A CONCRETE TIE

Photographs from concrete ties removed from the derailment site and other areas in the railway industry show a wear pattern that has a triangular shape with loss of material on the field side of the tie. This shape and the type of abrasion shown indicate that the tie was over loaded on the field side and only one-half of the available bearing area was taking up the applied loads. Figure 1 shows the triangular abrasion pattern with the black lines highlighting the abrasion shape. Figure 2, from an internal BNSF report, is the measured profile of an abraded concrete tie from a recent Amtrak derailment showing that the abrasion, still in a triangular pattern, within one inch from the gage side shoulder [6].

Figure 1. Triangular abrasion pattern in a concrete tie with black lines outlining a triangular pressure distribution assumed for this analysis.

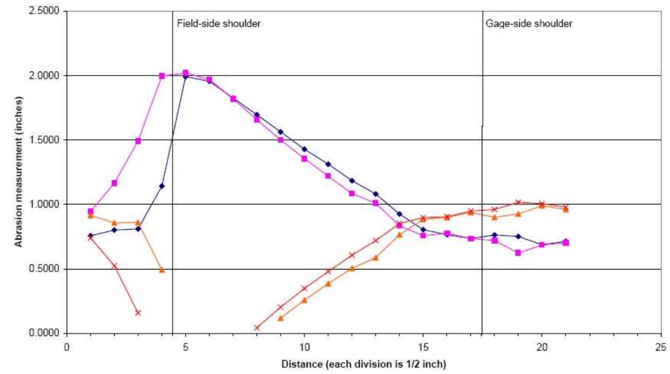

Figure 2. Concrete tie rail seat abrasion measurements.

Modeling, Assumptions and Calculations,

Calculation for the rail seat pressure was modeled similar to a foundation footing with a vertical load and a moment applied at the centerline. As modeled, the rail base was considered the footing resting on the foundation, the rail seat. Depending on the vertical load magnitude and direction of applied moment, as determined by the location and magnitude of applied vertical and lateral loads, the pressure distribution can vary from triangular to trapezoidal to rectangular [7]; a triangular shape is shown in Figure 3. When the rail moment is zero the pressure distribution is rectangular and is equal to the applied vertical load divided by the bearing area. If the eccentricity (e = applied moment divided by total vertical load) falls within the middle third of the rail base the pressure distribution is trapezoidal, given by equation (1) for gage side and equation (2) for the field side. When the eccentricity falls outside the middle third of the rail base then the pressure distribution has a triangular shape and is given by equation (3).

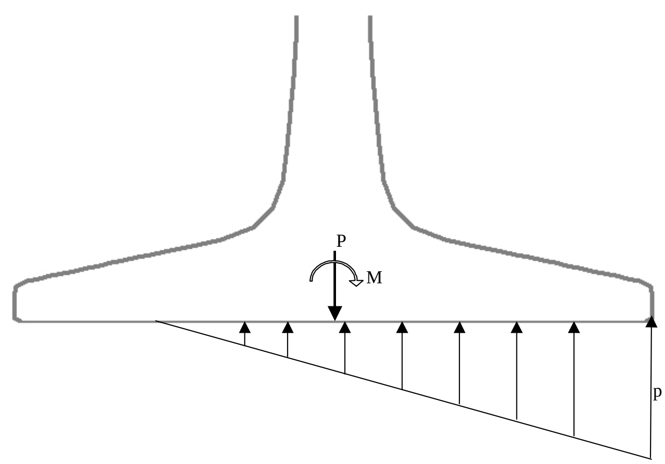

Figure 3. Vertical, moment, and an assumed rail seat pressure distribution on a concrete tie, L/V resultant is outside the middle third of the rail base.

$$\mathbf{p_g = \frac{P}{b}\left(1 - \frac{6e}{b}\right)} \qquad (1)$$

$$p_f = \frac{P}{b}\left(1+\frac{6e}{b}\right) \qquad (2)$$

$$p_f = \frac{2P}{3(b/2-e)} \qquad (3)$$

Where b = Rail base width

P = Centerline vertical load

e = Eccentricity is the applied moment divided by the vertical load (M/P)

p = Pressure at the edge of the rail, subscript f and g indicate field and gage side, respectively.

The maximum pressure can occur under the rail gage or field side depending on the direction of the applied moment at the rail centerline, usually the direction and magnitude of the applied lateral load controls the moment direction. If the lateral load is to the field side then the maximum pressures occurs at the field side of the rail base while if it is to the gage side then the maximum pressure occurs at the gage side of the rail base. Equation (1) and (2) as given are for a lateral load to the field side.

The applied vertical and lateral loads used in this analysis were determined from NUCARS™ model for a section of concrete tie track with two reverse curves using an Amtrak P-42 locomotive. The pressure distribution was calculated using the above equations and the loads developed from the model. Since the tie pads cannot carry any moment it was assumed that the rail pad distributed the load over the same area as the rail base bearing area. The major effect of the pad would be the attenuation of high dynamic loads, but it is not expected that the pad would distribute the applied load over a wider area than the rail base.

Vertical and lateral loads calculated from track geometry measured by a track geometry vehicle with normal wheel cant for a track section approximately 1000 feet long were converted to a vertical force and applied moment at the rail centerline. Using the converted loading and the above equation the maximum pressure for field and gage side were calculated. This pressure was then factored to account for the rail tie bearing area depth, 7.5 inches, typical for a concrete tie. A reduction factor of 0.49 applied to the calculated pressures to account for the vertical wheel load distribution to a single tie [8]. This factor eliminates loads carried by adjacent ties due to the bending stiffness of the rail.

Figure 4 represents the pressure on the field and gage side around a recent Amtrak derailment. The derailment is around the 1560-foot marker. At this location, the concrete stress contact from the wheel rail load predictions excides the allowable concrete stress. Under these conditions, it would be expected that the concrete would begin to fail and produce a pattern as those seen at the site and depicted in figure 1. For worn rail or deteriorated tie condition, these loadings combinations could be worse.

Figure 5 presents a distribution of the pressure versus the number of occurrences over this 1000 feet track section. Figure 6 is a plot of percent occurrence of the field and gage side pressures.

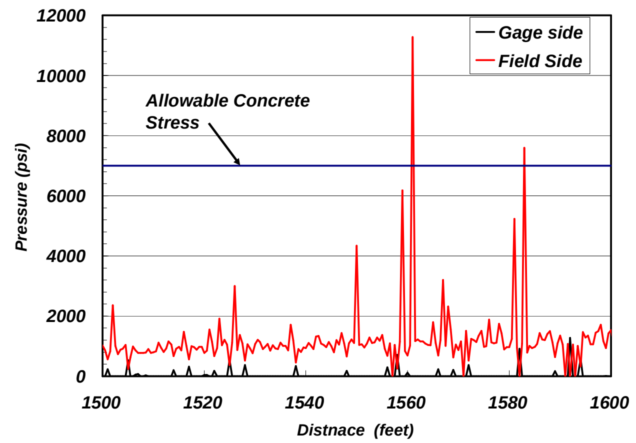

Figure 4. Field and gage side pressures around the derailment site.

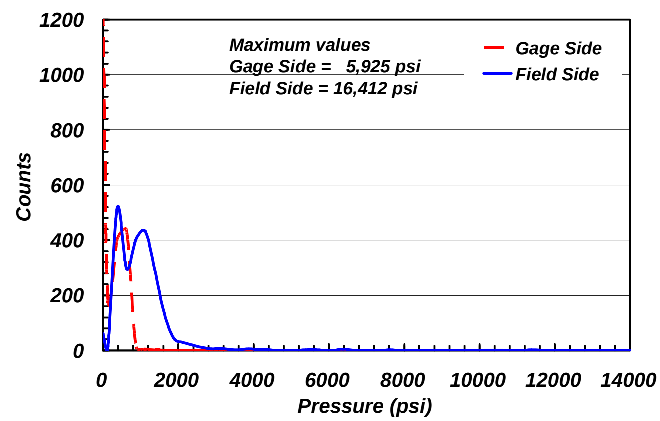

Figure 5. Concrete tie field side and gage side rail seat pressure distribution.

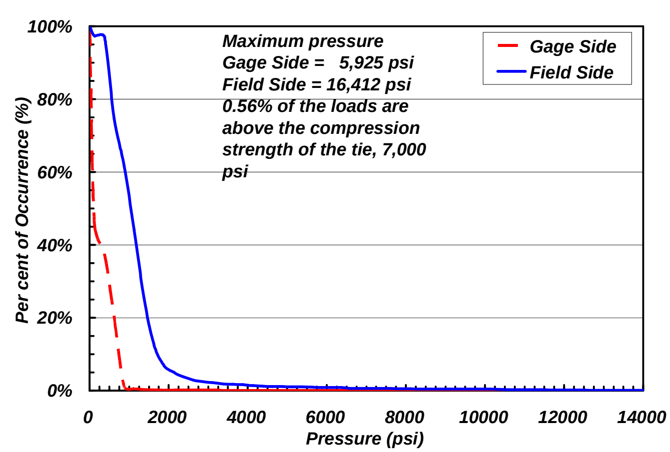

Figure 6. Field and gage rail seat pressure distribution as percent of occurrence.

Two basic assumptions made for this analysis are:

1. Once the L/V resultant was within a tenth of an inch from the edge of the rail base it was assumed that the rail was at the overturning point. This was to take into account the rail base radius and to eliminate the very high pressures calculated in the analysis from an unstable condition that exists at the point of rail overturning. At the overturning point, the entire load is supported on an edge of the rail along its length over the tie.
2. It was further assumed that the elastic fasteners had lost their hold down capacity or were missing.

The maximum pressures based on this analysis and assumptions were 5,925 psi for gage and 16,412 psi for field side. While the gage side pressure is within the design limits of most concrete ties, 7,000 psi [9], the field side maximum pressure exceeds this limit by a factor greater than 2. Average pressure for the gage side is approximately 400 psi with similar values for the field side with the exception of a secondary peak around 1,200 psi and higher pressures beyond the design limit. It is believed that these pressures beyond the design limit are the driving forces for rail seat deterioration.

The percentile of pressure that exceeded the design limit, 7,000 psi, is 0.56%. This is a small number but it is consistent with isolated locations where this type of deterioration has been found. The breakdown of concrete due to exceeding the concrete compressive strength under repeated loadings would occur at isolated locations where geometry irregularities caused high load levels. The correlation of excessive pressures due to track geometry imperfections and abraded ties at this site provides an explanation why RSA is occurring. Even at lower load levels, concrete tie rail seat abrasion is initiated. Once abrasion is initiated then other factors such as foreign material between the concrete tie pad and tie and moisture will accelerate this process.

USE OF MEASURED ABRASION TO CALCULATE TRACK GAGE UNDER LOAD.

Charts Development and Parametric Studies

The need to measure and control rail seat abrasion on concrete ties has become apparent with two recent Amtrak derailments. Methods to detect areas that have excessive rail seat abrasion and present a safety issue are under investigation by FRA. Data collected on geometry cars is considered as an alternative method for identifying critical locations. However, for these measurements to be reliable the required frequency of inspections may be too high based on the availability of existing geometry cars. A simpler method is being considered for field forces, either FRA or railroad inspectors, to evaluate a site once it has been detected by a geometry car or during a visual inspection by an inspector. One such a method is to use “an abrasion measurement gauge” to measure the void between the rail and tie. This value than can be converted to an additional displacement to be added to the track gage due to rail roll at the abraded location. The contribution of rail roll can be added to the measured gage to assure that the total gage under abraded condition meets the safety limits.

Figure 7, shows one rail seat abrasion measurement device currently available. Other similar devices or a rules/tape can be used to measure concrete tie abrasion. This gage fits between the abraded tie and the rail base to measure concrete tie abrasion. Other similar feeler gages or a ruler can be used in the absence of a specific measuring device.

Figure 7. A Typical rail abrasion measurement device

The Charts developed here are designed to convert measured concrete tie rail seat abrasion, measured by a feeler gage or any other similar device, to expected gage when the rail is seated under vehicle loads. This is accomplished by adding the gage change due to the rail roll caused by the rail seat abrasion to the static measurement of gage and comparing it to the gage limit. The rail rotation due to rail seat abrasion is shown in Figure 8 for the five possible cases of concrete tie rail seat abrasion that are found in high curvature track. A description of each case is given in Table 1. Figure 9 is a chart that converts the measured rail seat abrasion to additional track gage for the five different cases of concrete tie abrasion. All cases described here are subject to the abrasion measurements taken at the field side between the rail base and the concrete tie. Two readings are required one on each side of the concrete tie as viewed from the field side to the centerline of the track.

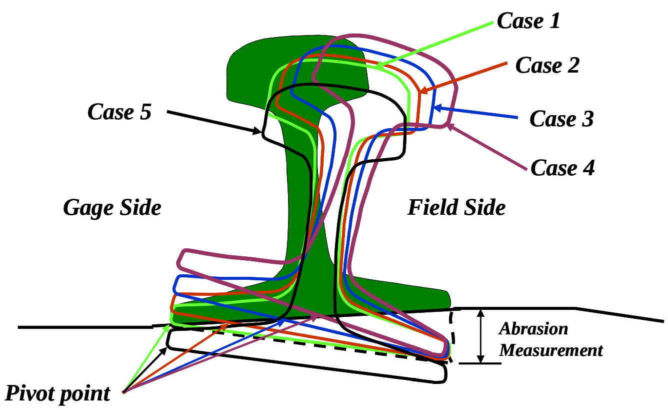

Figure 8. Five possible cases of concrete tie abrasion.

Table 1. Typical rail seat abrasion cases on concrete ties used in this analysis.

Case	*Description*
1	The rail pivot point is on the gage side base edge and there is a uniform rate of abrasion over the entire rail seat.
2	The rail pivots is approximately 1 inch from the gage side rail base edge and the abrasion is uniform over the remaining length of rail seat.
3	Same as in case 2 but the rail pivots approximately 2 inches from the gage side rail base edge.
4	The rail pivots at the centerline of the rail base with uniform abrasion to the field side edge of the rail seat.
5	Abrasion pattern as in case 1 with an additional measurable abrasion at the gage side of the rail

Five new rail sections were considered for evaluation, 119, 132, 133, 136, and 140 RE. Two of the five rail sections, 119 and 133 RE, for case 3, pivot at the centerline are shown in Figure 10. The curves for the remaining rails fall between these two curves shown in the figure. All rails show the same trend with small variation due to rail base and rail height dimensions. The variations are sufficiently small that one curve can be developed from all rails under consideration. Based on the small variations between rail sections, 136 RE rail was selected for the analysis of each of the five cases given in Table 1 and the results are given in Figure 9. Rails of smaller section, i.e., 115 RE and smaller are not usually used on concrete tie track and are excluded from this study.

The curves indicate that the worst case is when the rail pivots about the centerline of the rail while the pivot point at the gage side rail base is the most benign of all the cases. The affected rail base length controls this change as the pivot point moves from gage side to the centerline of the rail. Regardless of which case of abrasion is considered if there is an inch measured rail seat abrasion there could be an addition of 1c to 2¼ in. gage widening.

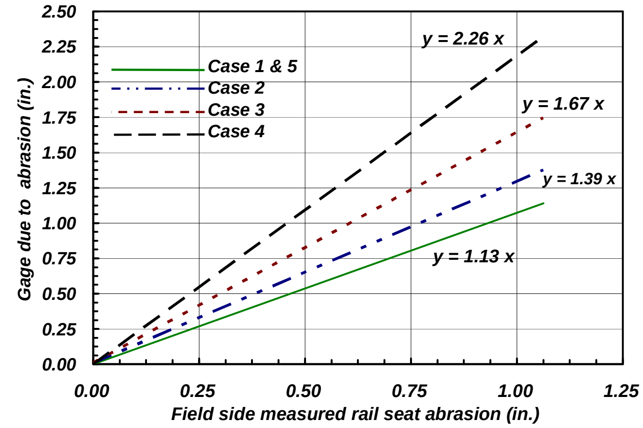

Figure 9. Recommended charts to calculate loaded gage at location with concrete tie rail seat abrasion.

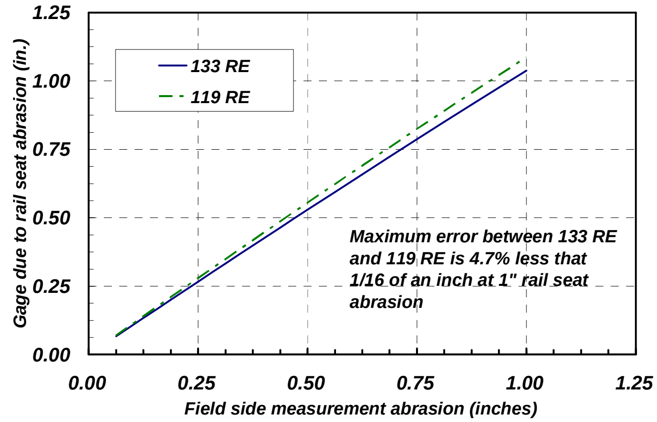

Figure 10. Additional Track gage comparison between rail sections with the rail pivot point at centerline.

Results from a parametric study to analyze the variation between four different rail sections and the pivot point at the rail centerline (case 4) are shown in Figure 10. The differences between the various rail sections are very small. Maximum difference at 1.0 inch measured rail seat abrasion is less than 3/16 of an inch or approximately 4.7 percent. The same was found for the pivot point at the gage corner with the maximum difference of less than 1/16 of an inch or approximately 4.9 percent. Based on this result, one curve was developed for each level of abrasion for all the rail section and each curve is presented in Figure 9 along with an equation of the line.

Recommended Measurement Procedures

This analysis is based on the measurement of abrasion taken at the field side of the rail base. Two measurements should be taken one on each side of the tie and an average value used as the measured abrasion. Once this measurement is known, estimate the pivot point from the gage side rail base to within one inch. If there are signs of gage side abrasion but not sufficient to measure it must be assumed, the rail is pivoting on the gage side rail base. If the rail seat area at the gage side shows no sign of abrasion then further inspection is required to determine which of the remaining three levels is applicable. A small mirror can be used to check under the rail base to locate the initiation of abrasion, estimate, or measure the distance from the gage side rail base edge and select the appropriate case discussed above.

With the measured abrasion value and pivot level use Figure 10 or use the equation to determine an additional gage under vertical and lateral loads. As an example, if the measured abrasion is ½ inch and the pivot is determined that the pivot point is 1 inch away from rail base gage side then the additional gage added to the measured track gage is e”.

The case where there is abrasion on both sides of the rail seat (the rail is floating between adjacent ties), measure both gage and field side abrasion. Measure the field side abrasion as described above. Measure the gage side abrasion by taking measurements at both sides of the abraded tie and average them to produce a single value. If the values are within 1/8 of an inch of from each other or the gage side abrasion is greater than the field side, the measured track gage should be considered the gage under vertical and lateral loads. This is a 1/8 of an inch within the measurement error of the gage and if the gage side is less than the field side, the gage will decrease under load. If it is not the case, subtract the gage side abrasion from the field side and use this as the measured abrasion value. Then use the first case, pivot at the gage side rail base, to calculate the additional gage to be added to the measure track gage.

As an example if the gage side abrasion is measured at ¼ of an inch and the field side is measured at c of an inch, no additional gage needs to be added to the track gage to calculate the loaded gage. However, if the field gage was ½ inch by subtracting the gage side measured abrasion there is a net ¼ inch abrasion on the field side. Using the net measured abrasion and case one the additional gage added to the measured track gage from Figure 9, is approximately ¼ inches.

Taking the additional gage widening due to rail abrasion and considering the worst case scenario, (case 4), a maximum rail seat abrasion allowed for concrete ties was calculated for all the classes of track found in the Track Safety Standard (TSS). The maximum values were calculated for three rail wear cases; new rail, ¼-inch, and ½-inch rail wear. The results are shown in Table 2. For Excepted track through Class 2, the maximum allowed abrasion is no more than ½ inch for new rail; however concrete ties are seldom used for these classes of track. For classes of track 3 through 5 the loaded gage is within limits for new rail if the abrasion is less than 3/8 of an inch. Other than dedicated high speed track, concrete ties are predominately found in these classes of track. For classes of track from 6 through 9, found in subpart G of the TSS the maximum abrasion allowed on the field side is 5/16” for new rail.

The conditions described and the values given in table 2 are based on case 4, worst-case scenario, and three rail wear limits, new, ¼, and ½. These values are somewhat restrictive, but due to the uncertainty of the pivot point location on the abraded rail seat, these values are warranted at this time. As measurement methodologies improve, either from automated inspection vehicles or hand held devices, then the curve given in Figure 9 and values in Table 2 can be adjusted to reflect the new field data.

Thus, it is recommended that for any concrete tie abrasion measurement exceeding the limits given in table 2 appropriate remediation as prescribed in the TSS should be applied to the section of track.

Table 2. Maximum abrasion table for each class of track found on the track safety standards based on maximum change of gage, case 4.

Class of track[1]	Gage must beat least[1] (inches)	but not more than[1] (inches)	Change of gage with in 31 feet must not be greater than[1] (inches)	Maximum allowable field side concrete tie abrasion[2] for new rail (inches)	Maximum allowable field side concrete tie abrasion[2] for ~¼” worn rail (inches)	Maximum allowable field side concrete tie abrasion[2] for ~½” worn rail (inches)
Exempt	N/A	58.25	N/A	11/16	9/16	8/16
1	56.00	58.00	N/A	9/16	8/16	6/16
2	56.00	57.75	N/A	8/16	6/16	5/16
3	56.00	57.75	N/A	8/16	6/16	5/16
4	56.00	57.50	N/A	6/16	5/16	3/16
5	56.00	57.50	N/A	6/16	5/16	3/16
6	56.00	57.25	.50	5/16	3/16	2/16
7	56.00	57.25	.50	5/16	3/16	2/16
8	56.00	57.25	.50	5/16	3/16	2/16
9	56.25	57.25	.50	5/16	3/16	2/16

1. Gage limits found in TSS, Part 213, Subpart C, Track Geometry and Subpart G, Train Operations at Track Classes 6 and Higher
2. Abraded values are based on worst-case scenario where only half of the rail seat is abraded from the rail centerline to the field side of the rail base.

CONCLUSIONS AND RECOMMENDATIONS

Combinations of vertical and lateral wheel forces resulting from track geometry irregularities can cause a new type of rail seat deterioration characterized by a loss of material under the field side of the rail. The identification and elimination of the combinations of track geometry irregularities that result in these high forces may not be practical or may require more frequent track geometry surveys than are reasonable. To mitigate this problem, new ties could be constructed to be capable of withstanding higher load combinations and/or tie pads could be developed that more effectively spread high loads reducing stress concentrations under the field side rail edge. For existing ties, the focus must be on prediction of deterioration, the detection of severe deterioration and the repair of the rail seat area in the field.

The rates of abrasion once initiated should be studied to assure that even vehicles under normal curving and dynamics loads do not overstress the tie. As the tie continues to abrade, the bearing area decreases which in turn accelerates the pressure leading to wider gage due to rail rotation.

Since this research indicates that this problem is not the classical abrasion found on concrete ties but a crushing problem due to overstressing the concrete; the rate of abrasion should be determined to assure that safety is maintained between current inspection cycles. The rate could be very high and non-linear especially when the entire rail base is abraded and expose concrete aggregates are crushed by the applied loads.

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